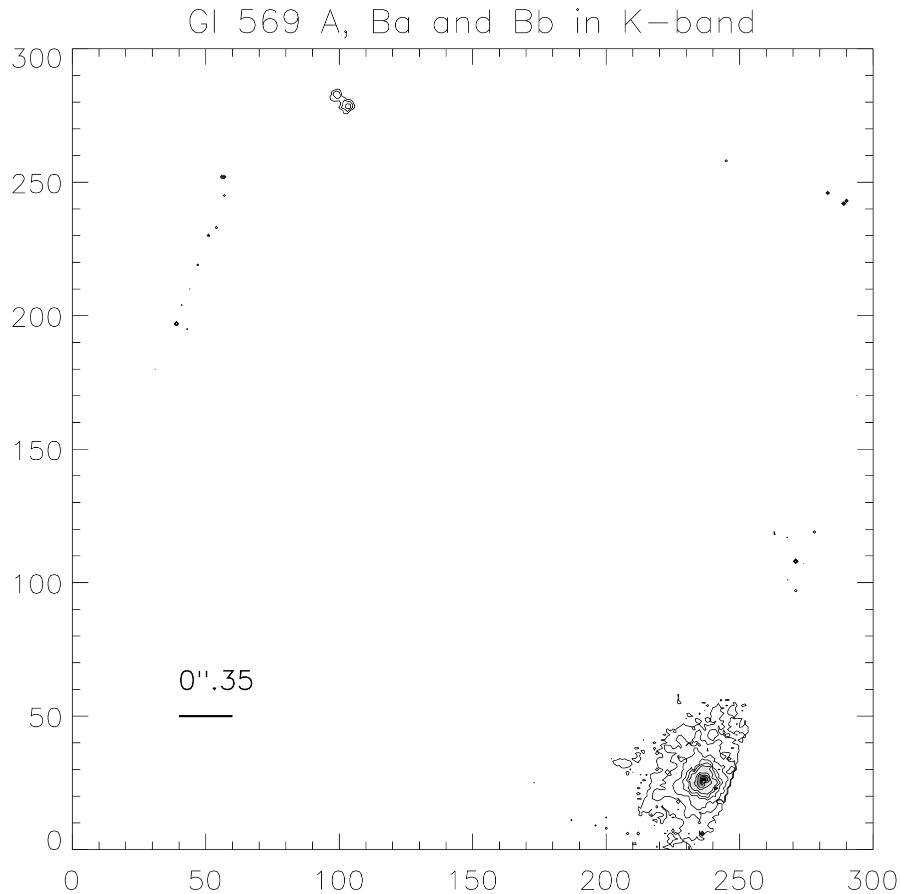
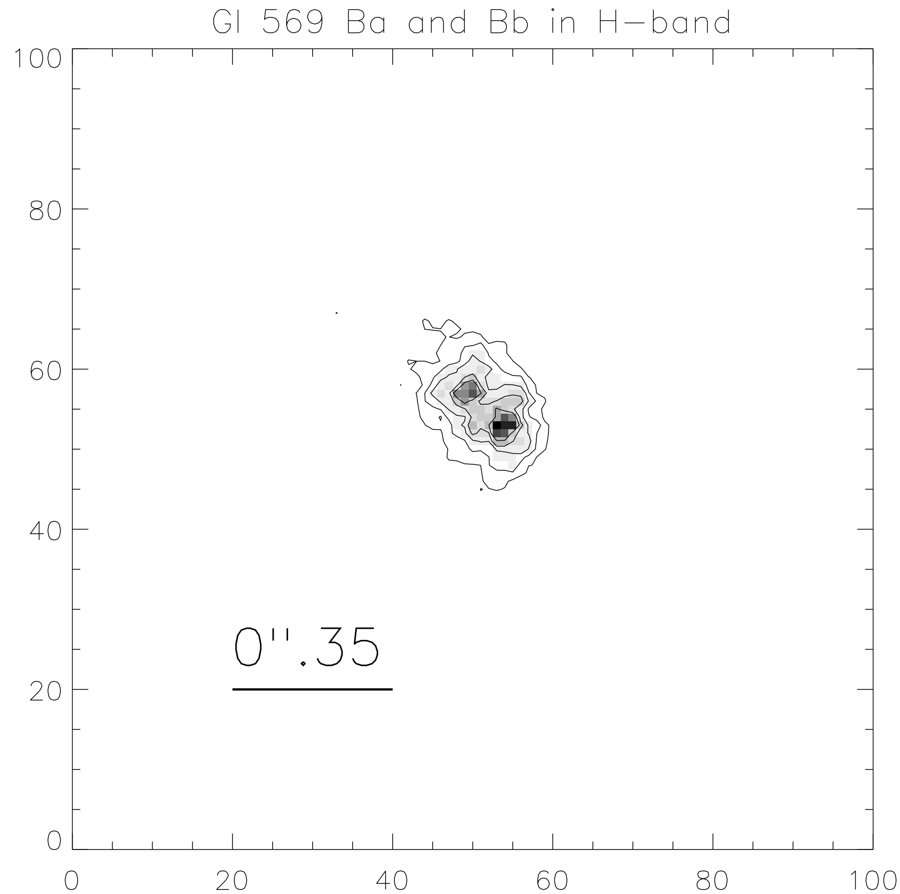


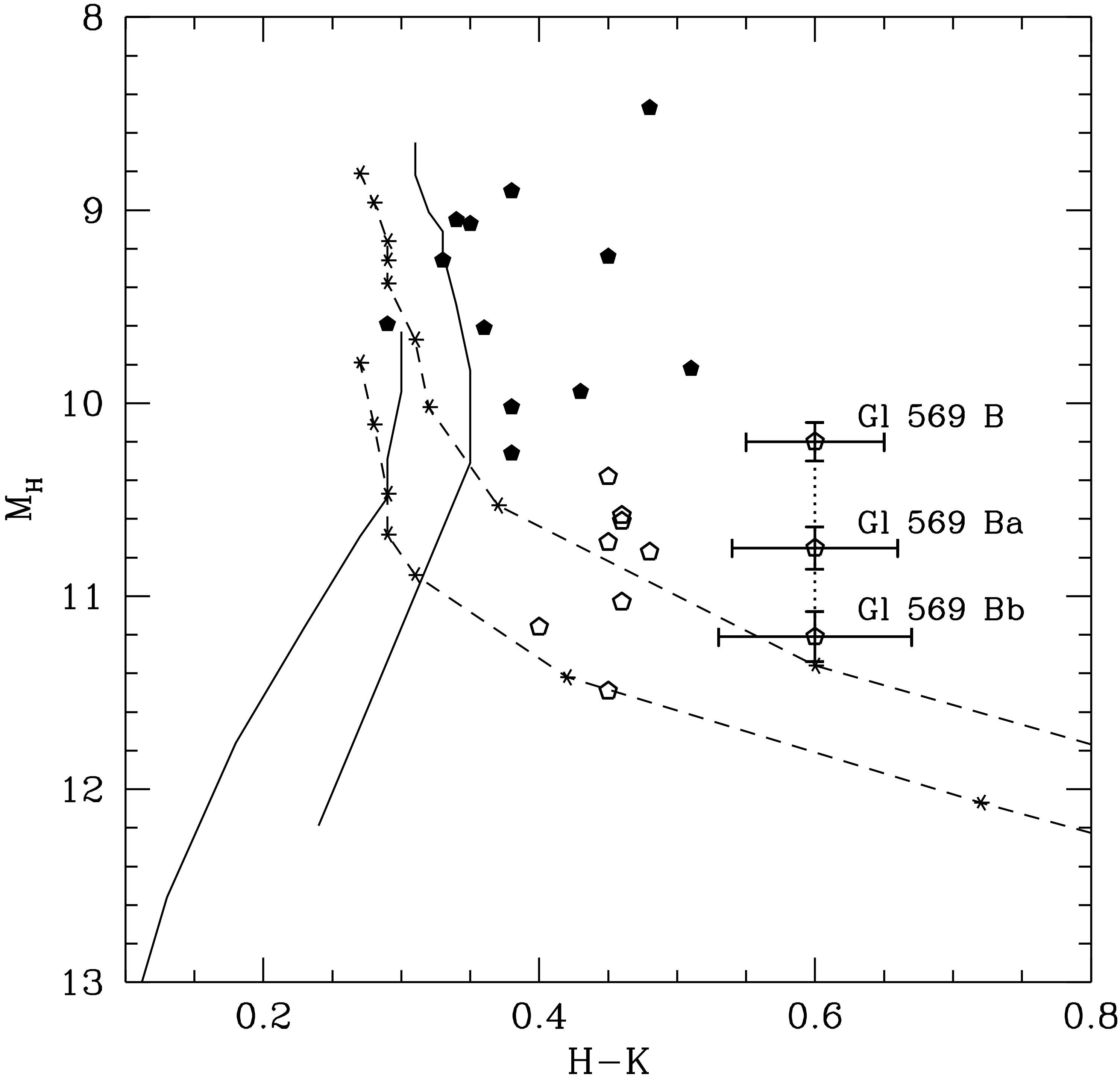
Gl 569 A, Ba and Bb in K−band
0''.35
0
50
100
150
200
250
300

Table 1. Gl 569 multiple system data

Components	Δm_J	Δm_H	$\Delta m_{K'}$	Separation	PA
Gl 569 A-Ba	5.8±0.1	4.9±0.1	4.8±0.1	5".00±0".01	25^o
Gl 569 Ba-Bb	0.5±0.2	0.5±0.1	0.5±0.1	0".101±0".002	48^o



Gl 569 Ba and Bb in H–band
0''.35



8
9
10
11
12
13
0.2
0.4
0.6
0.8
H−K
M_H
Gl 569 B
Gl 569 Ba
Gl 569 Bb

The Discovery of a Companion to the Very Cool Dwarf Gl 569 B with the Keck Adaptive Optics Facility

E. L. Martín, C. D. Koresko, S. R. Kulkarni, B. F. Lane

Division of Geological and Planetary Sciences, California Institute of Technology, MS 150-21, Pasadena, CA 91125

and

P. L. Wizinowich

W. M. Keck Observatory, 65-1120 Mamalahoa Highway, Kamuela, Hi 96743

contact e-mail address: ege@gps.caltech.edu

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ABSTRACT

We report observations obtained with the Keck adaptive optics facility of the nearby (d=9.8 pc) binary Gl 569. The system was known to be composed of a cool primary (dM2) and a very cool secondary (dM8.5) with a separation of 5" (49 Astronomical Units). We have found that Gl 569 B is itself double with a separation of only 0".101±0".002 (1 Astronomical Unit). This detection demonstrates the superb spatial resolution that can be achieved with adaptive optics at Keck. The difference in brightness between Gl 569 B and the companion is ∼0.5 magnitudes in the J, H and K' bands. Thus, both objects have similarly red colors and very likely constitute a very low-mass binary system. For reasonable assumptions about the age (0.12 Gyr–1.0 Gyr) and total mass of the system (0.09 $M_{\odot}$–0.15 $M_{\odot}$), we estimate that the orbital period is ∼3 years. Follow-up observations will allow us to obtain an astrometric orbit solution and will yield direct dynamical masses that can constrain evolutionary models of very low-mass stars and brown dwarfs.

Subject headings: surveys — binaries: general — stars: formation — stars: evolution — stars: low-mass, brown dwarfs — individual: Gl 569

1. Introduction

Substellar objects do not have enough mass to settle on the hydrogen-burning main sequence, and therefore their luminosity and surface temperature are very age dependent. The substellar mass limit has been determined with theoretical models. For solar composition, Kumar (1963) obtained a limiting mass of 0.07 $M_\odot$. Recent determinations using non-gray model atmospheres reached a similar result (0.075 $M_\odot$; Baraffe et al. 1998). The limiting mass is larger for low metallicity.

Lithium is a fragile element in stellar interiors that gets destroyed at temperatures below those necessary for hydrogen fusion. Very low-mass (VLM) stars and brown dwarfs (BDs) with masses above $\sim$0.060 $M_\odot$ destroy their initial lithium reservoir while they are fully convective. BDs with masses below $\sim$0.06 $M_\odot$ never burn lithium (Magazzù, Martín & Rebolo 1993; Nelson, Rappaport & Chiang 1993). Spectroscopic observations of BD candidates can detect lithium if this element has been preserved, and provide information about the mass of the object. This is the so-called lithium test for BDs, first proposed by Rebolo, Martín & Magazzù (1992). Although early lithium searches in low-luminosity dwarfs were unsuccessful (Martín, Rebolo & Magazzù 1994; Marcy, Basri & Graham 1994), the test gave positive results in the Pleiades open cluster, confirming the existence of free-floating BDs (Rebolo et al. 1996). The combination of lithium abundances, effective temperatures and luminosities with evolutionary models provide the only means of estimating ages and masses for single VLM stars and BDs (Tinney 1998; Martín, Basri & Zapatero Osorio 1999). However, these masses rely on theoretical models that have not been well tested. Perhaps the strongest test to the models comes from binary systems where masses can be measured from the orbital parameters. The most accurate mass determinations are derived from eclipsing binaries. The problem is that they are rare. No VLM stars or BDs are known to belong to an eclipsing binary system.

Wide binaries also yield dynamical masses. With the advent of high spatial resolution instrumentation (Hubble Space Telescope, hereafter HST; adaptive optics, hereafter AO; speckle techniques; interferometry) it is possible to resolve binaries with smaller separations and consequently shorter periods. Leinert et al. (1994) discovered with speckles a BD candidate companion to the dM5.5 nearby star LHS 1070. The spectral type of the companion is dM8 (Leinert et al. 1997) and the orbital period is about 20 years. Martín, Brandner & Basri (1999) found with HST the first resolved binary system (separation = 0".275 or 5 AU) where both components are L-type BDs. They estimated that the orbital period could be about 30 years. Two more L-type binaries with slightly larger separations have recently been found by Koerner et al. (1999) using Keck near-infrared imaging. Two BDs companions are also known with separations of several arcseconds from early-M stars (Nakajima et al. 1995; Rebolo et al. 1998).

Gl 569 is a nearby star (d=9.8 pc) with high levels of chromospheric and coronal activity. Forrest, Skrutskie & Shure (1988) reported a possible BD companion separated 5" from the primary. Henry & Kirkpatrick (1990) obtained a low resolution spectrum and classified it as an M8.5 dwarf. They estimated a mass of 0.09 $M_{\odot} \pm 0.02$ $M_{\odot}$. Magazzù et al. (1993) did not detect lithium in Gl 569 B, even though its position in the HR diagram suggest that it is a very young object. In this paper we show that Gl 569 B is a binary, and hence the Gl 569 system is at least triple. We estimate that the orbital period of the VLM binary could be about 3 years for a circular orbit, or shorter for an elliptical orbit, implying that dynamical masses can be obtained in a relatively short time.

2. Observations, Data Analysis and Results

We observed with the Keck II Adaptive Optics Facility (KAOF) on August 28th, 1999. The instrument has been described elsewhere (Wizinowich et al. 1998). We used

the KCAM camera, which has a plate scale of 0".0175 pix^{-1} and a square field of view of 4".5 x 4".5. Flatfield correction was made using twilight exposures. Sky subtraction was performed using images of a field adjacent to Gl 569 observed inmediately after the science images. We used the DAOPHOT package available in the IRAF environment for data reduction and analysis.

Using a neutral density (ND2; attenuation of ∼100) filter and co-adding short exposures, we were able to detect the fainter components of the multiple system in the J, H and K' filters without saturating the primary. The primary star is not double and serves as a PSF reference in the field. In Fig. 1 we show a 60 s exposure on KCAM, consisting of 30 co-adds, in the K'-band. Gl 569 A looks asymmetric because it is cut off by the edge of the detector, but it is clearly not double or elongated in the same orientation as Gl 569 B. The edge of the detector does not correspond to the drawn box. We have rotated the frame by 251 degrees and transposed it in order to present the image of the binary in the standard orientation where North is up and East to the left. Using Gl 569 A, we estimate Strehl ratios of 9%, 20% and 40% in the J, H and K' filters (with ND2 filter), respectively. We also obtained 18 images in the H-band (without ND2 filter) of Gl 569 B alone, with the primary out of the field of view. The two components of the binary system were clearly resolved in all the frames. In Fig. 2 we show a typical exposure of 3 seconds. Each contour line represents half the intensity of the previous one, and the lowest is 2% of the maximum intensity.

Any ghost from Gl 569 Ba would likely not be of comparable magnitude to the object (Gl 569 Bb has about 65% of the flux of Gl 569 Ba). Moreover, if Gl 569 Bb were a ghost from Gl 569 Ba there would likely also be a nearby ghost for Gl 569 A of the same relative magnitude, but there isn't. That means that any ghost would have to have Gl 569 A as its source. This is ruled out by the fact that we moved and rotated the binary on

the detector, observing it in three different quadrants, and the separation and magnitude difference between Gl 569 Ba and b remained the same. Furthermore, the contrast in the J-band between Gl 569 A and Gl 569 Ba is larger than that in the K-band by 1 magnitude (Table 1) because of the cooler temperature of the latter object. If Gl 569 Bb was a ghost due to Gl 569 A, it should have the same color. However, we find that Gl 569 Bb has similar color than Gl 569 Ba, indicating that it is a cooler object than Gl 569 A.

We obtained relative astrometry and photometry by fitting the point spread function with a gaussian function. The results are listed in Table 1. No photometric standard was observed in the same night. Therefore, we present differential magnitudes only, which are based on a 150 s J-band frame, a 30 s H-band frame and a 60 s K'-band frame (all taken with an ND2 filter in the beam). We also measured the H differential magnitude in the dithered exposures of 3 s without ND2 filter, and found the same value as in the image with the ND2 filter. The J-H and H-K' colors of both components of Gl 569 B are the same within our error bars. It is not surprising that VLM dwarfs with similar absolute magnitudes have nearly identical colors. The likelihood that the companion to Gl 569 B is a background star is less than 0.1% because of the very low-density of late M dwarfs and giants within the small volume covered by our images. The galactic latitude of Gl 569 is quite high (+59.4 degrees). In fact, no objects other than those of the Gl 569 system appear in any of our frames.

3. Discussion

Forrest et al. (1988) presented IHK photometry for Gl 569 B. They noted that the object is more luminous than other field dwarfs of similar temperature, and attributed it to young age. However, Magazzù et al. (1993) failed to detect lithium in it, and constrained its age to be older than 0.1 Gyr and the mass to be larger than 0.06 $M_{\odot}$. The fact that

this object is a binary solves the problem of undertanding why it is overluminous but has depleted lithium. The relatively high luminosity is due to its binary nature, with components of similar brightness, not to a very young age. Nevertheless, as discussed below, the system is probably not old.

We have combined the absolute photometry provided by Forrest et al. (I=13.88±0.2; H=10.16±0.1; K=9.56±0.1) with our differential magnitudes (Table 1) to place Gl 569 Ba and Bb in a color-magnitude diagram (CMD). In Fig. 3, we compare Gl 569 B with other very late M dwarfs in the Pleiades and the field, which have infrared photometry available in the literature (Festin 1998; Leggett, Allard & Hauschildt 1999; Zapatero Osorio, Martín & Rebolo 1997). A trend of increasing H-K color for fainter M_H can be seen in the CMD, but there is considerable dispersion.

Allard et al. (1997), Hauschildt et al. (1999), and Allard (1999) have presented model atmospheres for ultracool dwarfs in the temperature range 3500 K to 1500 K. The Nextgen set does not include any dust effects, while the Dusty set includes dust formation and settling. We have used theoretical isochrones computed using Nextgen and Dusty atmospheres (Chabrier & Baraffe 1999) for comparison with the data in Fig. 3. The Nextgen isochrones are too blue and do not fit the fainter and redder objects. The Dusty ones give a better fit, but the two components of Gl 569 B do not fall onto the same isochrone. The problem could be due to the presence of strong steam absorption in the H-band which is not well reproduced by the models (e.g. Allard 1999). Another possibility is that Gl 569 Ba is itself an unresolved binary. Follow-up high-resolution spectroscopic observations are needed to test this hypothesis.

The Gl 569 B system must be older than the Pleiades cluster (age∼0.11 Gyr; Martín et al. 1998) because of the lack of lithium in its optical spectrum. On the other hand, the system is probably not very old because Gl 569 A has strong radio and X-ray emission

(Pallavicini, Tagliaferri & Stella 1990). The high level of chromospheric and coronal activity suggests a young age because the star is apparently single. In particular, it is not a tidally locked spectroscopic binary (Marcy & Benitz 1989). The position of Gl 569 Bb in the CMD close to the Dusty isochrone for 0.1 Gyr may also indicate youth. For the purpose of estimating the orbital period of the system, which is of interest for follow-up observations, we assume that the age is in the range 0.12 and 1 Gyr. We derive for the components of Gl 569 B absolute K-band magnitudes of 10.15±0.12 and 10.60±0.12 from Forrest et al.'s absolute photometry and our differential photometry. According to the Lyon Dusty models, for an age of 0.12 Gyr, the masses that correspond to those absolute K magnitudes are 0.051 $M_\odot$ and 0.042 $M_\odot$, respectively. For an age of 1 Gyr, the corresponding masses are 0.087 $M_\odot$ and 0.062 $M_\odot$. While Gl 569 Ba could be either a VLM star or a massive BD, depending on its age, Gl 569 Bb is likely to be substellar. A lithium detection in Gl 569 Bb would be very interesting for constraining its age.

The total mass of the system inferred from the Lyon models is 0.15 $M_\odot$ for an age of 1 Gyr. Assuming that the observed separation is close to the mean semimajor axis, we estimate an orbital period of 2.58 years. For an age of 0.12 Gyr, the total mass is 0.09 $M_\odot$, and the period is 3.33 years. Basri & Martín (1999) have determined that the short-period BD binary PPl 15 has a very eccentric orbit. The period of Gl 569 B could be shorter if the orbit has a very large eccentricity because it is more likely to catch it near apastron than near periastron. We plan to reobserve it for detecting the orbital motion. The orbital parameters of Gl 569 B will allow us to determine if the components have substellar masses. It will also be a first point in the mass-luminosity relationship for dwarfs later than M8. This binary system is a powerful test for evolutionary models of VLM stars and BDs.

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Figure Captions:

Fig. 1.— A 60 s K' image with neutral density filter. The two faint components of the Gl 569 B system are detected and the primary, Gl 569 A, is not saturated. Contours are peak counts $\times 2^{(9-n)}$. The faintest contour is 0.2% of the maximum peak. The plate scale is 0".0175 per pixel. The frame has been rotated so that North is up and East to the left.

Fig. 2.— A 3 s exposure of the Gl 569 B binary in the H-band. We show a subsection of 100 pix^2 of the full frame. Contours are peak counts $\times 2^{(6-n)}$. The faintest contour is 2% of the maximum peak. The orientation and plate scale is the same as in the previous figure.

Fig. 3.— An infrared color-magnitude diagram with the Lyon-group isochrones (Allard et al. 1997; Baraffe et al. 1998; Hauschildt et al. 1999) for ages of 0.1 Gyr and 1 Gyr. The solid lines are for Nextgen model atmospheres and the dashed lines are for Dusty models. Masses in solar units of 0.1, 0.09, 0.08, 0.075, 0.07, 0.06, 0.05, 0.04, 0.03 and 0.02 are marked with six pointed stars on the Dusty isochrones. Pleiades BD candidates are plotted with filled pentagons. Field very late M dwarfs of known distances are plotted with open pentagons. The three empty pentagons with error bars, joined with a dotted line, denote the position of Gl 569 B (combined light) and each of the two components resolved with the Keck AO system.